Combined EDL-Mobility Planning for Planetary Missions

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Outline

- Goals & Objectives
- Problem Statement
- Approach
  - Cost map
  - PDF
- Conclusions

Goals

- Develop data products that support decision making for **coupled, multi-opportunity EDL/Mobility problems**:
  - Site-specific decisions
  - Site selection motivated quantitative comparisons between different sites

- Provide an mission analysis/study tool for:
  - Systematic **tradeoff** between EDL and Mobility
  - Determining the relationship between selected **Figure-of-Merits** and key mission & system **parameters**

Framework for Coupled-Domain Mission Performance/Risk Analysis

Framework Elements

- End-to-end physics-based probabilistic models of performance
  ➔ Combined performance/risk analysis
- Coupled-domain trades/optimization
  ➔ Less over-design of the system for each phase/domain
- Principled mathematical approach
  ➔ Less likely to miss nonlinear performance/trade/effects
- High-fidelity models/simulations
  ➔ Defensible, quantitative results

Benefits to Mission

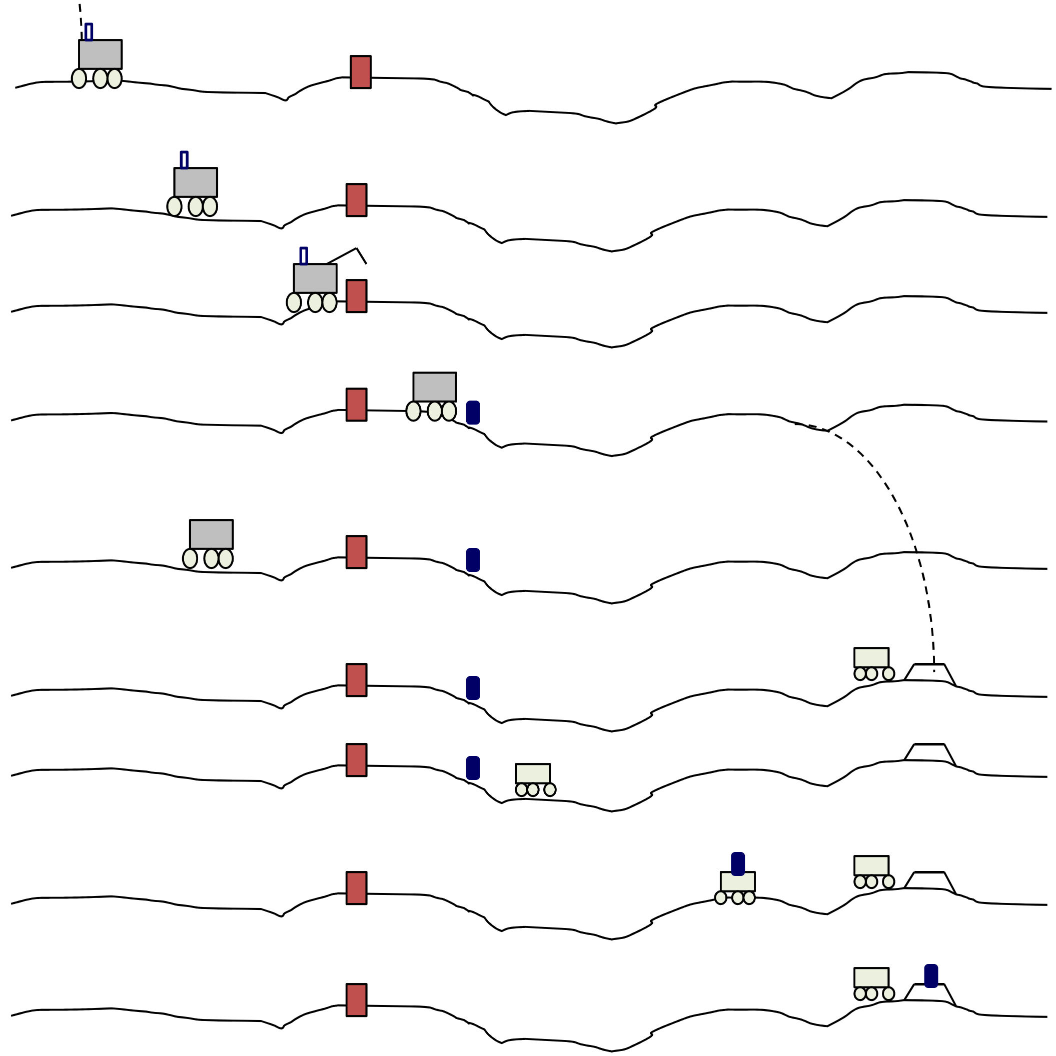
- Quantitative analysis/trades for more points in the architectural space
- Verify/optimize a cost-capped design for end-to-end performance/risk floor
- EDL/Rover System dependent (or independent) site-selection criteria
- Extensible to MSR-L MAV Ascent and MSR-O Orbital Rendezvous concept analysis

Objectives

- Develop a **probabilistic framework** that unifies consideration of EDL and Mobility performance
- Define **candidate EDL/Mobility problems** of interest to MSR concept studies and exercise the analysis framework
- Develop **interfaces to other study tools** and efforts (e.g. EDL Landing study/tools) so as to import data and probability distribution functions as needed into the MSR Study Tool
- Develop **extensions to the Multi-X concept** used in the EDL phase to take into account the subsequent mobility phase
- Develop **software to generate mobility related data products** to support the analysis
- Set up the **analysis capabilities for proposed MSR mission area**:10km-by-30km
- Demonstrate **initial capability** at a coarser resolution i.e. computational improvements are possible but not the focus here
- Note that current focus is *not* on the science data/sample acquisition phase but on the landing and mobility trades associated with getting to/from the science/cache target.

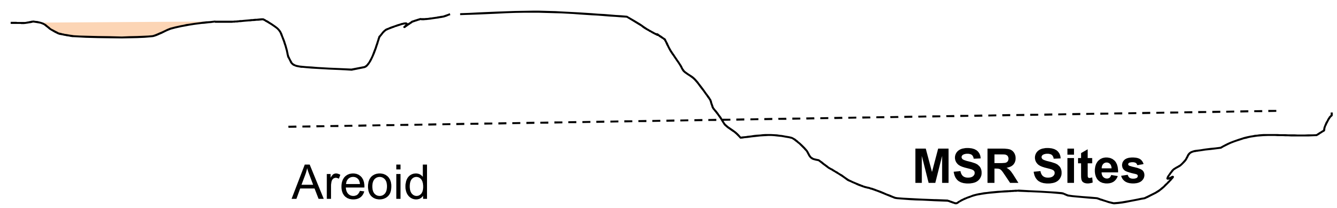
MSR Notional Scenario

- Sample Cache Rover (SCR) lands
- SCR drives to Science Target(s)
- SCR performs science & cacheing
- SCR drives to Cache Release / Rendezvous target & releases cache
- SCR continues on extended mission
- Sample Fetch Rover (SFR) lands
- SFR drives to Surface Rendezvous target
- SFR retrieves cache and returns to Lander
- SFR deposits cache into MAV



Proposed MSR Site Types

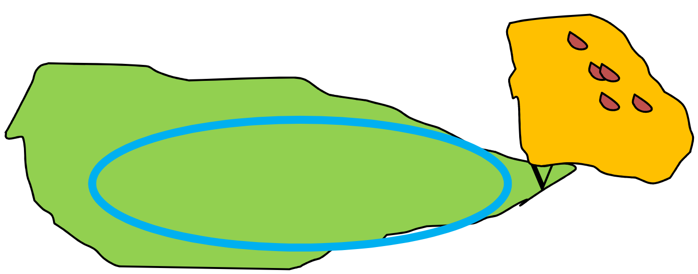
General Characteristics



Weathered away (exhumed) craters
Free of accumulated dust

"Go-To" Sites

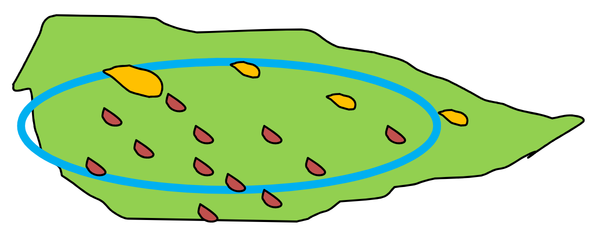
- Holden Crater



Land in safe region
Drive to science targets

"Sample-Locally" Sites

- Eberswalde Crater (hills with relief)
- NE Syrtis (rocky mesa edges, network of sand-dunes at angle-of-repose)



Land in scientifically rich region while avoiding isolated bad spots

Safe for landing | Unsafe for landing | Science targets | Landing Ellipse Target

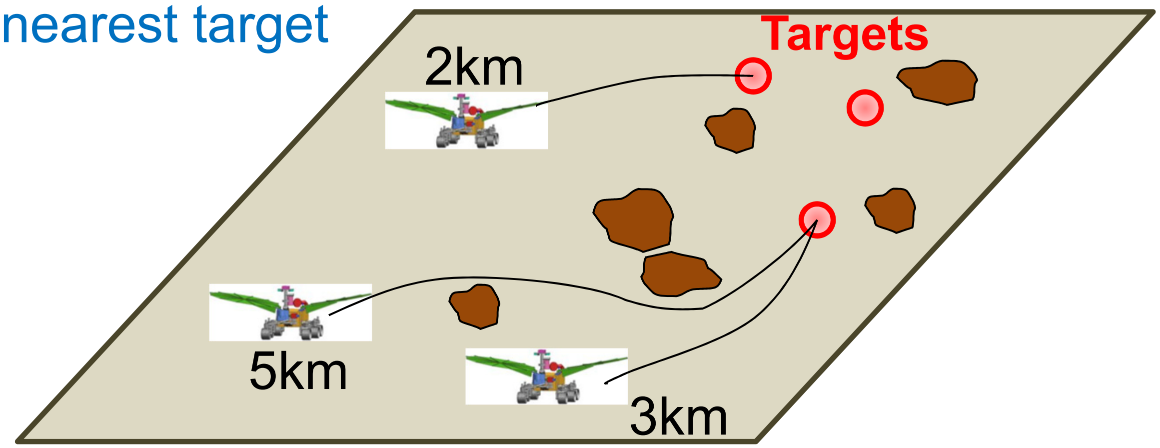
Hazards and Costs

Hazards

- For rovers - max drive slope, heights of rocks, terrain type
- For landers - max local slope at scale of lander diameter, hazardous rocks contained in lander radius sized circle

Cost-to-go

- For rovers – time, distance, wheel rotation with slip, obstacle proximity, risk penalty for hazardous/unknown regions etc., for moving from start to the nearest target

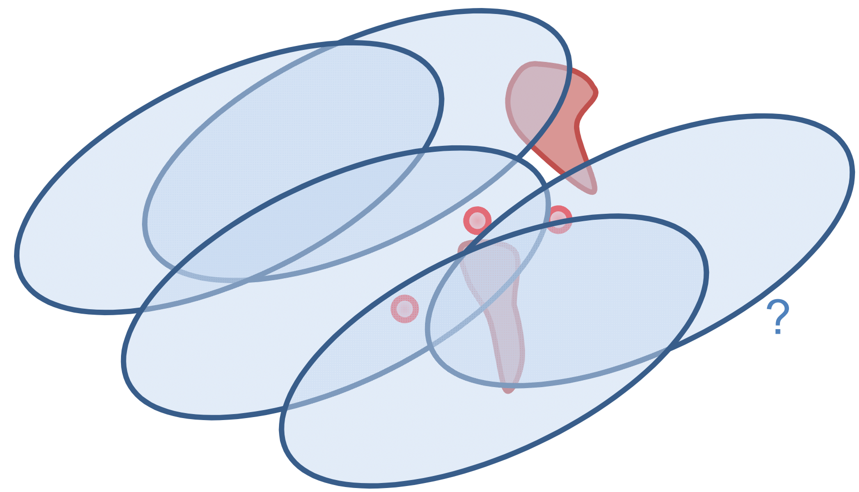


- For landers – safety of landing & consequences for subsequent mobility

Approach

Problem Statement

- Given
  - mobility hazards
  - landing hazards
  - landing PDF
  - science targets
  - vehicle parameters & initial conditions



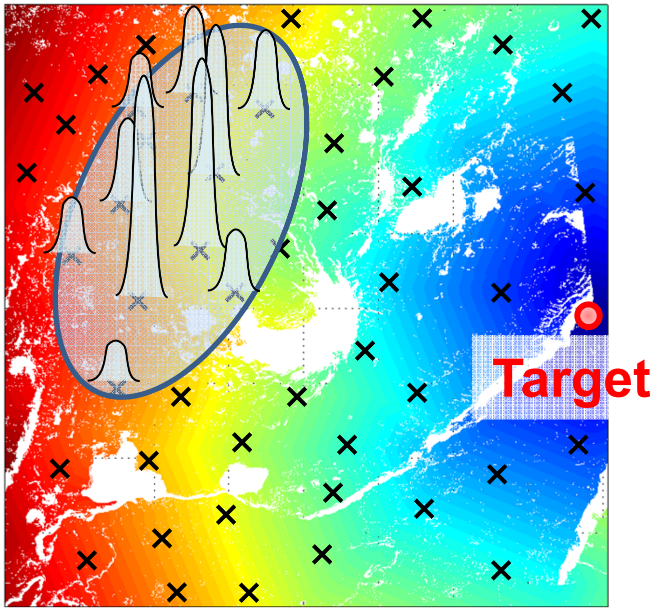
- Place the SCR landing ellipse target so as to:
  - minimize the expected drive distance
  - meet failure probability constraints

Note the additional functionality beyond MarsLS - computing a risk probability that **considers mobility activity after landing** and finding of the best landing ellipse target placement

Analysis Flow

- SCR mission sequence would be
  - Landing ellipse placement
  - EDL
  - Drive to target
- Planning goes backwards
  - Generate mobility cost-to-go map
  - Place multi-“X” for landing
  - Place a landing ellipse for landing
- Then, trade-off analysis
  - Simulate
  - Evaluate the performance
  - Change parameters/scenarios & repeat
- We will show 2D example w/ & w/o divert

Blue: Close to target
Red: Far from target



Cost Map Concept

Cost-to-go Map - A 2-D representation of decision making costs as a function of [x,y]

- Examples of decision making: "land at a good target point", “go to cache drop location target", "return to lander target location”
- Either directly used in the on-board decision making process or represents the effects of on-board decision making

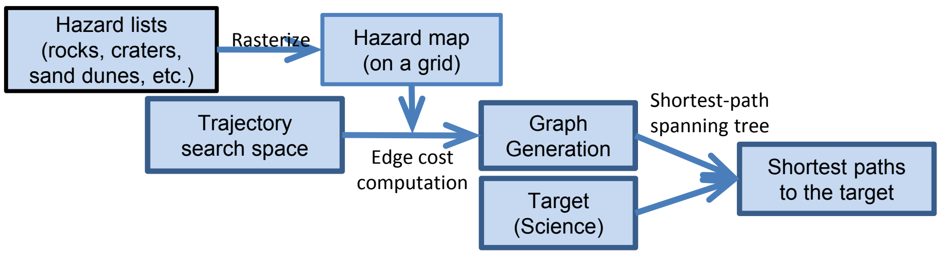
Mobility Cost-to-go Map

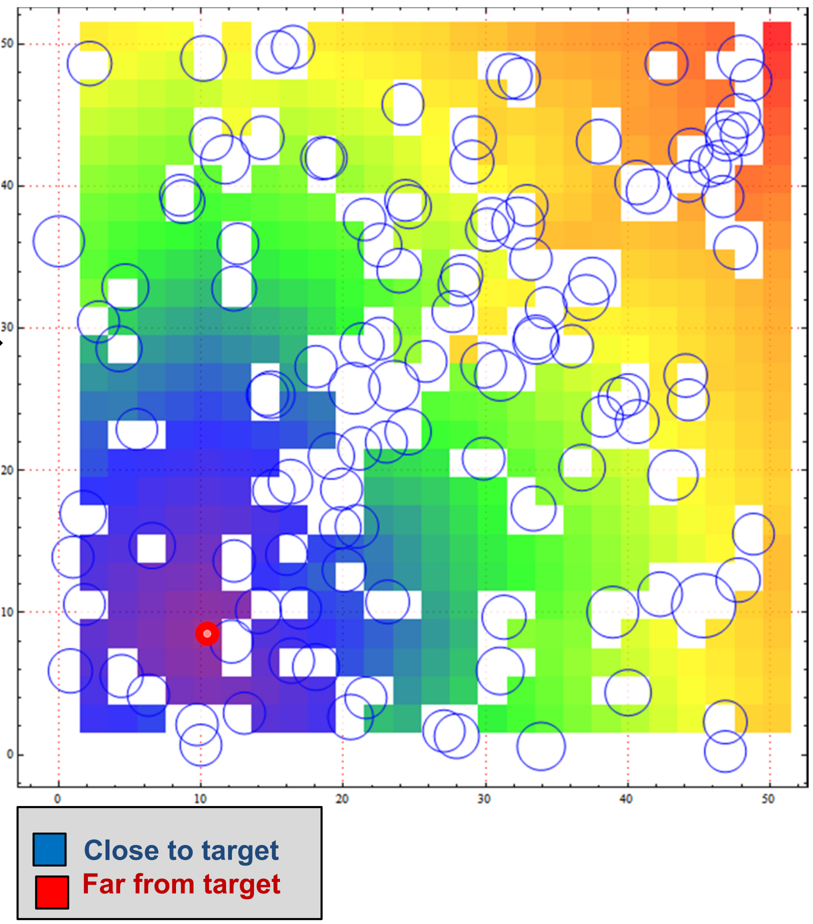
- Captures rover path traversability (i.e. encodes the on-board path selection/planning navigation) to store cost-to-go from [x,y] to target

EDL Cost-to-go Map

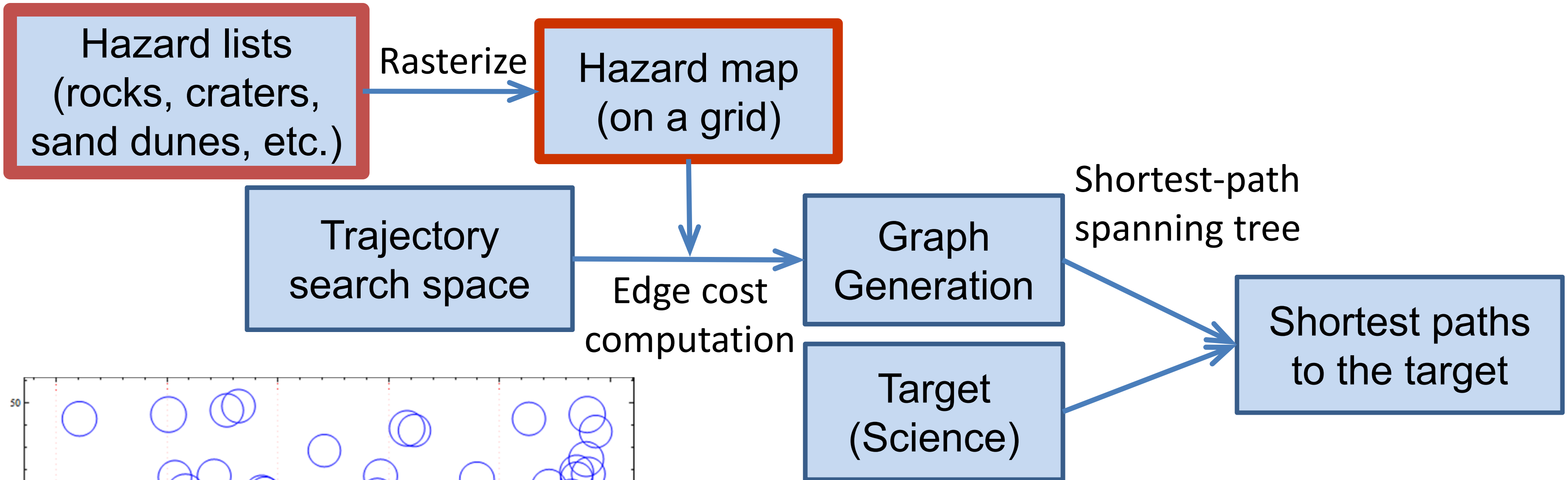
- Add hazard cost for a landing target at [x,y] (binary thresholded to 0, ∞) to mobility cost (e.g. distance or time-to-go) from [x,y] to mobility target

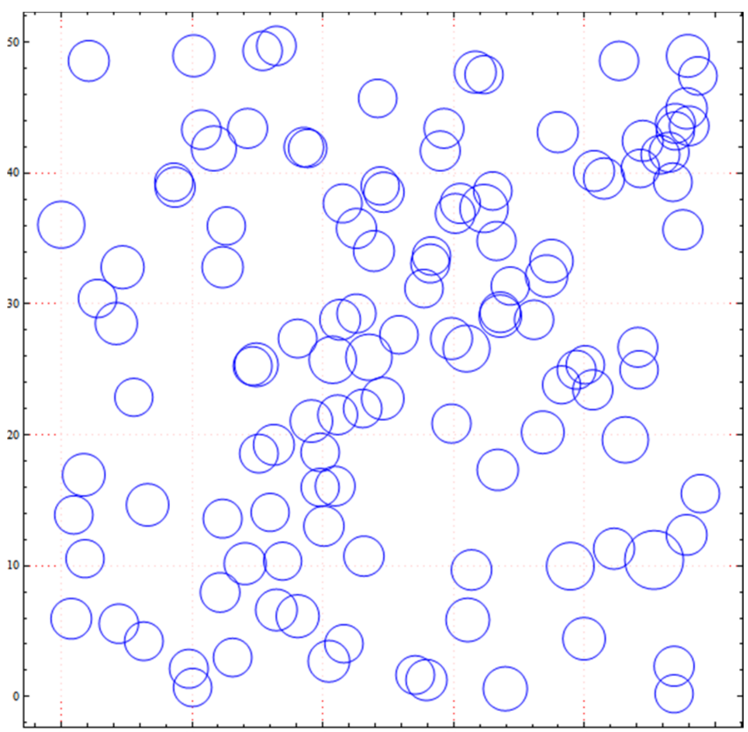
Mobility Cost Map





Mobility Cost Map – Hazard Data

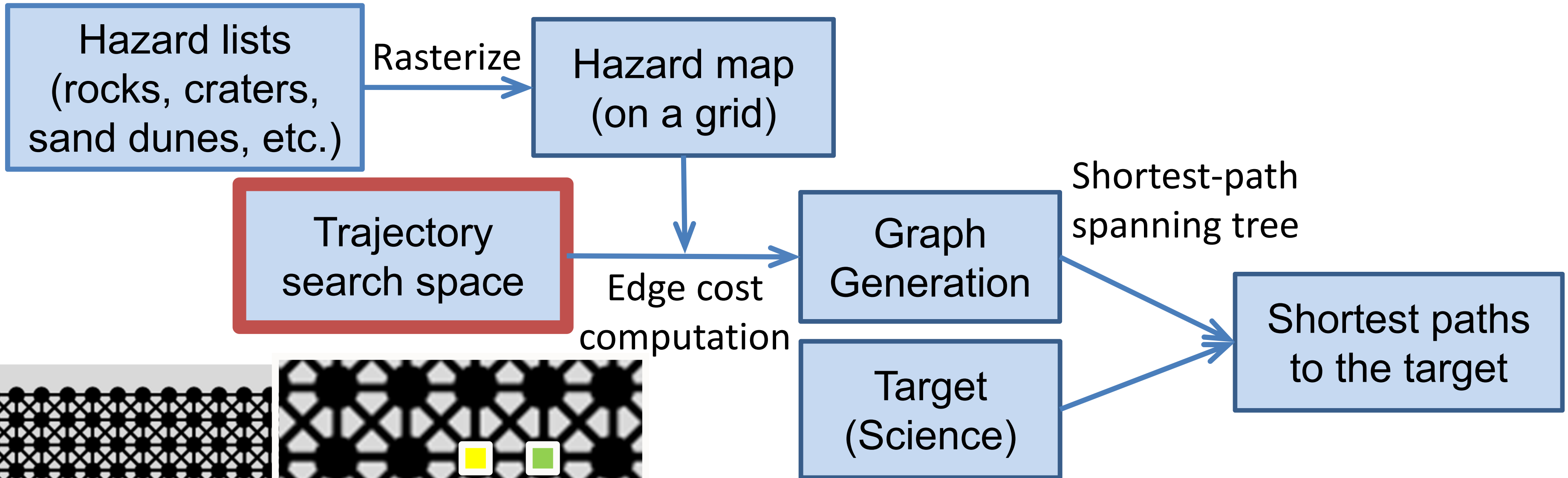


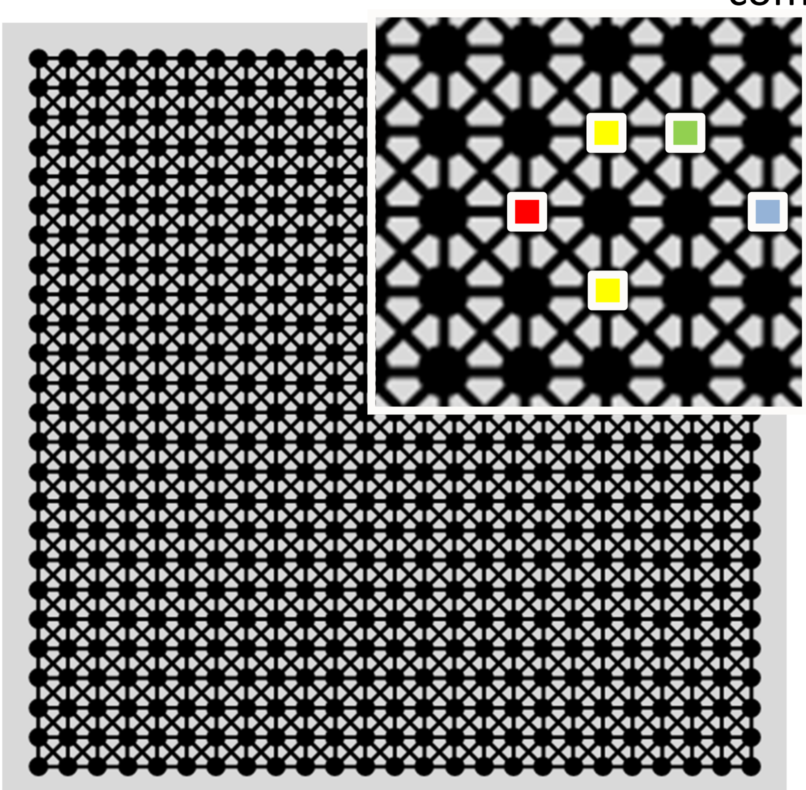


Golombek rock distribution

- Circular rocks
- Each rock expanded by the rover radius

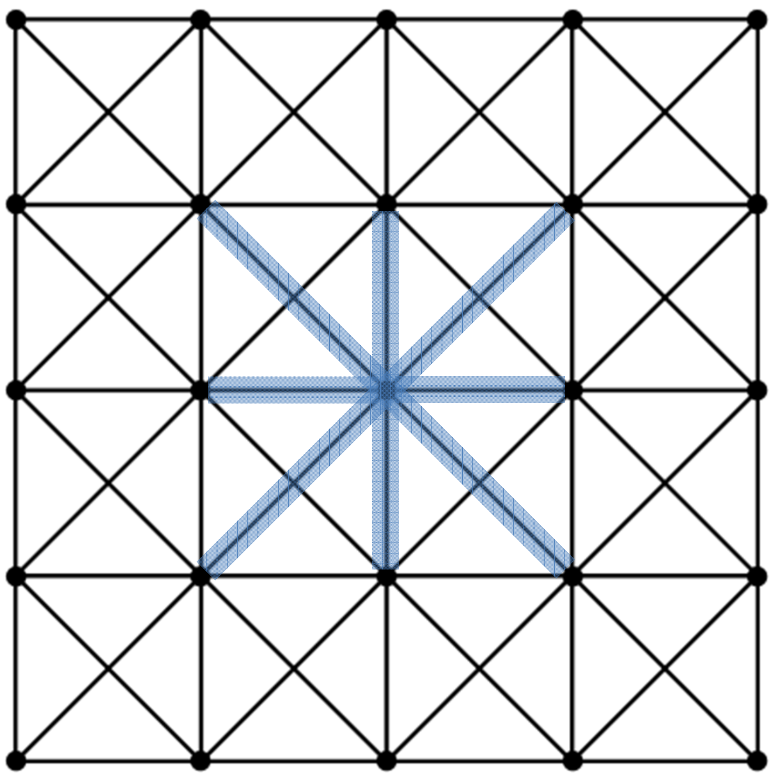
Mobility Cost Map – Search Space





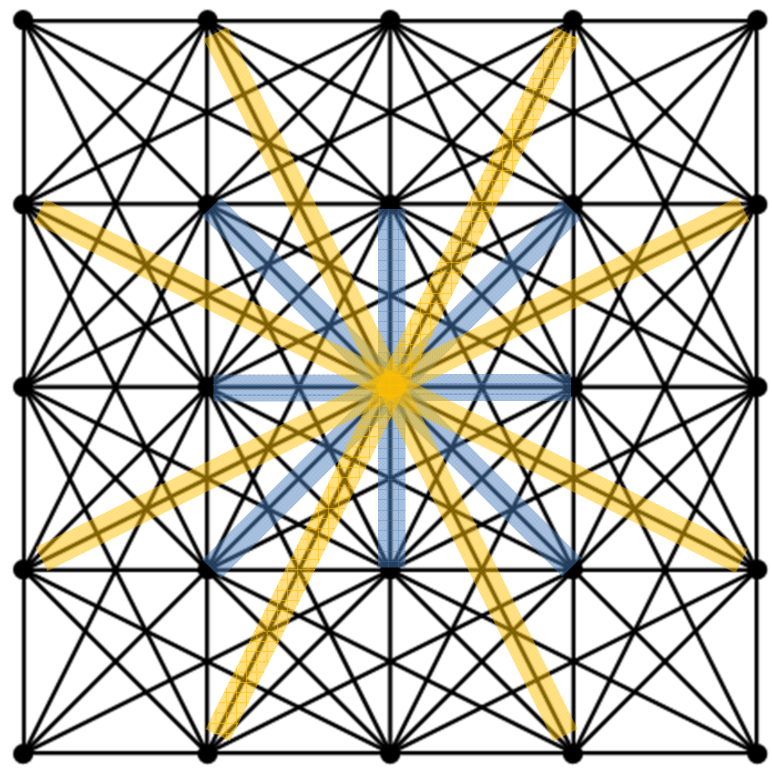
- 8-connected graph
- 1m grid spacing
- Minimum costs to the target:
  - Red: 0 (at the target)
  - Yellow: $\sqrt{2}$
  - Green: $1 + \sqrt{2}$
  - Blue: 3

8-connected grid



$$\text{Error} < \frac{(1+\sqrt{2})-\sqrt{5}}{\sqrt{5}} \sim 8\%$$

16-connected grid



$$\text{Error} < \frac{(2+\sqrt{5})-\sqrt{17}}{\sqrt{17}} \sim 2.7\%$$

Mobility Cost Map – Graph Generation

Hazard lists (rocks, craters, sand dunes, etc.)

Rasterize

Hazard map (on a grid)

Trajectory search space

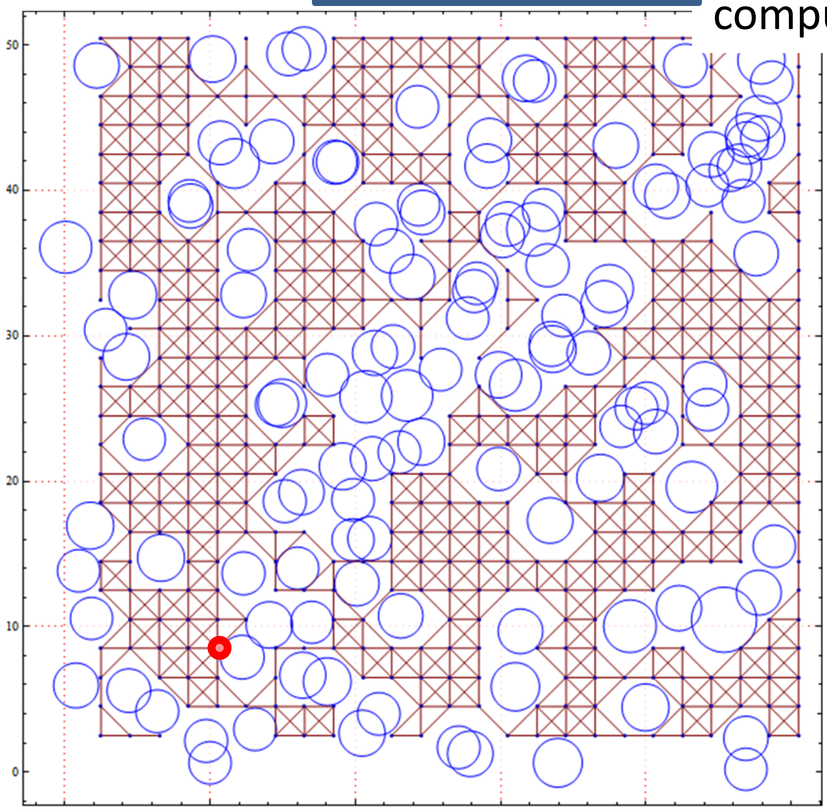
Edge cost computation

Graph Generation

Shortest-path spanning tree

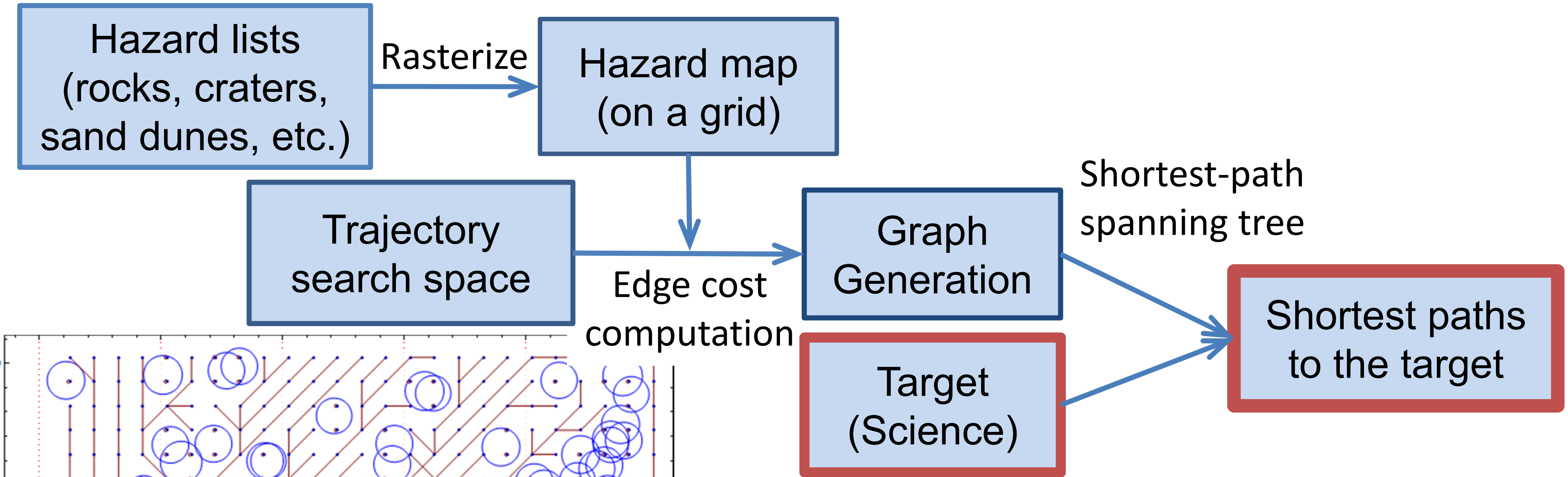
Target (Science)

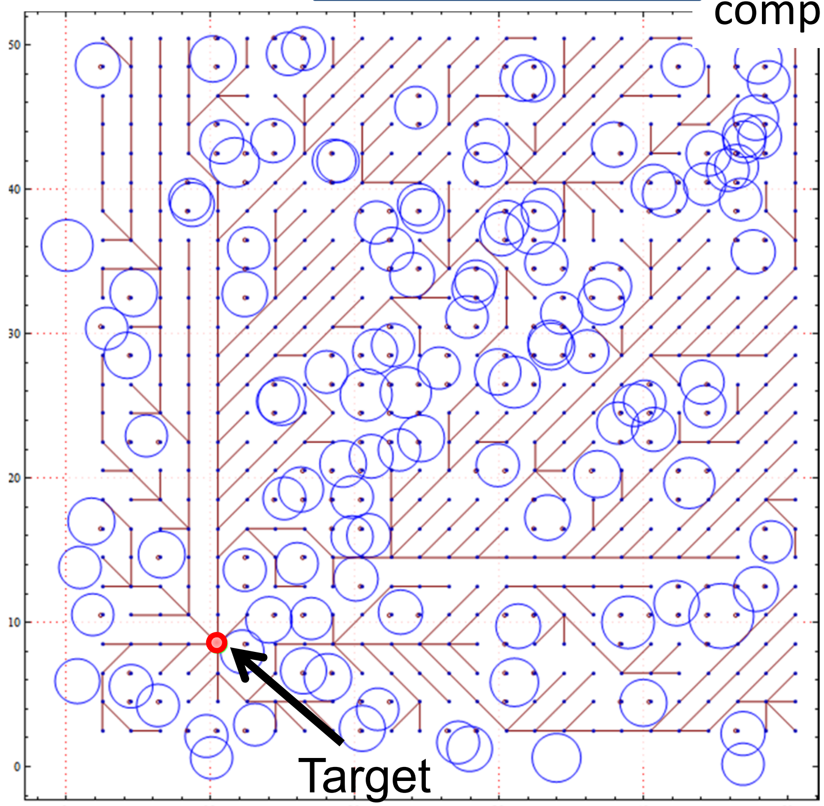
Shortest paths to the target



- Collision checks performed between rocks and each edge in path representation

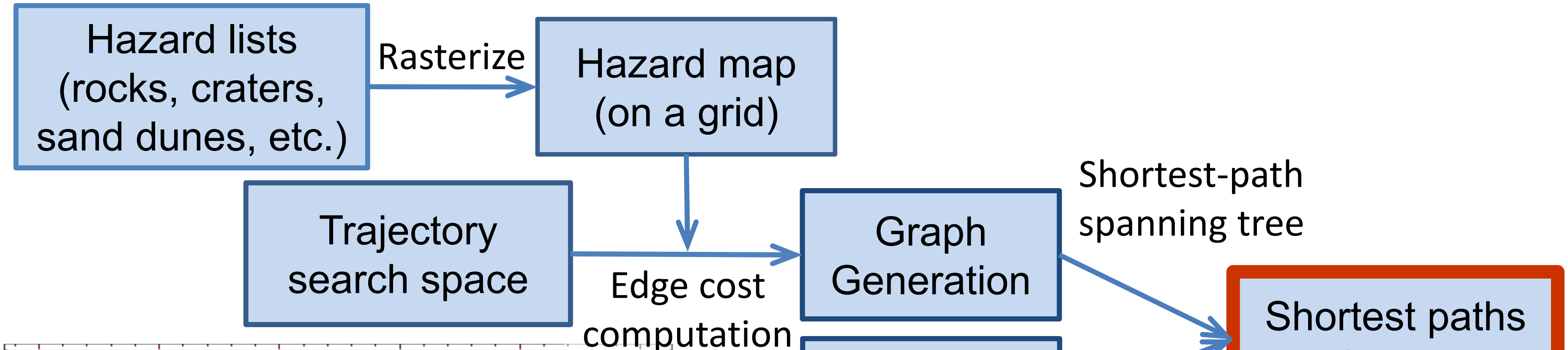
Mobility Cost Map – Minimum Cost Path

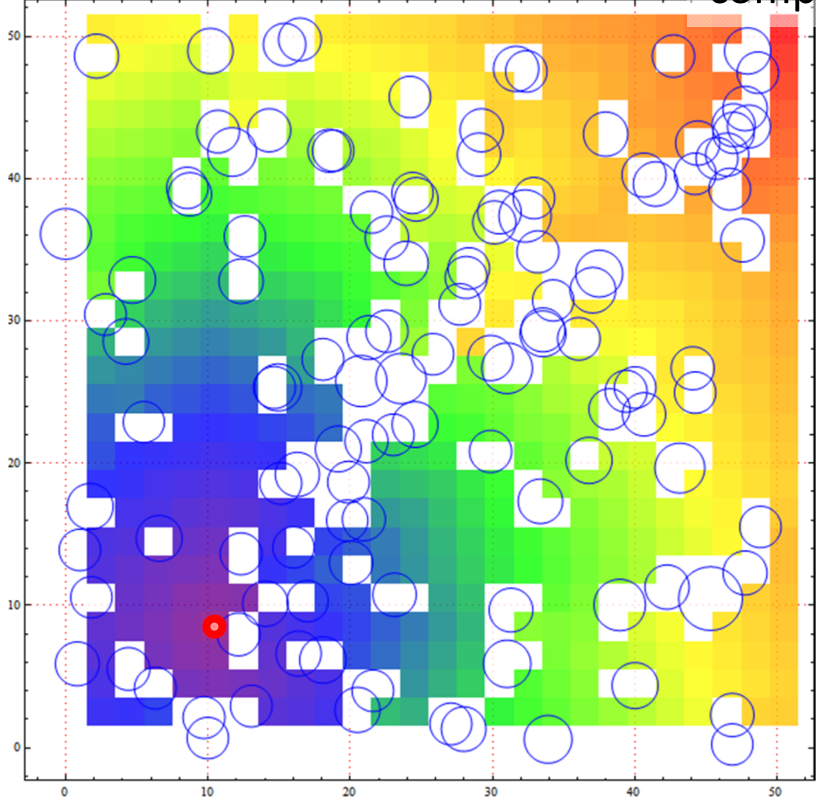




- Used Dijkstra’s algorithm
- Encodes cost and path to be selected from *any* point to the goal

Minimum Cost-to-go Map





- Convert costs from points generated by Dijkstra into a continuous map representation

➔ Repeat this for each target & take the minimum

PDF Processes

Parameters Cost Map

PDF input
(Entry States)

EDL Process
-changes PDF by **non-linear** aero-flight and touch-down dynamics, sensor noise induced knowledge errors & atmosphere/wind disturbance induced delivery errors

PDF Output
(Landed State)

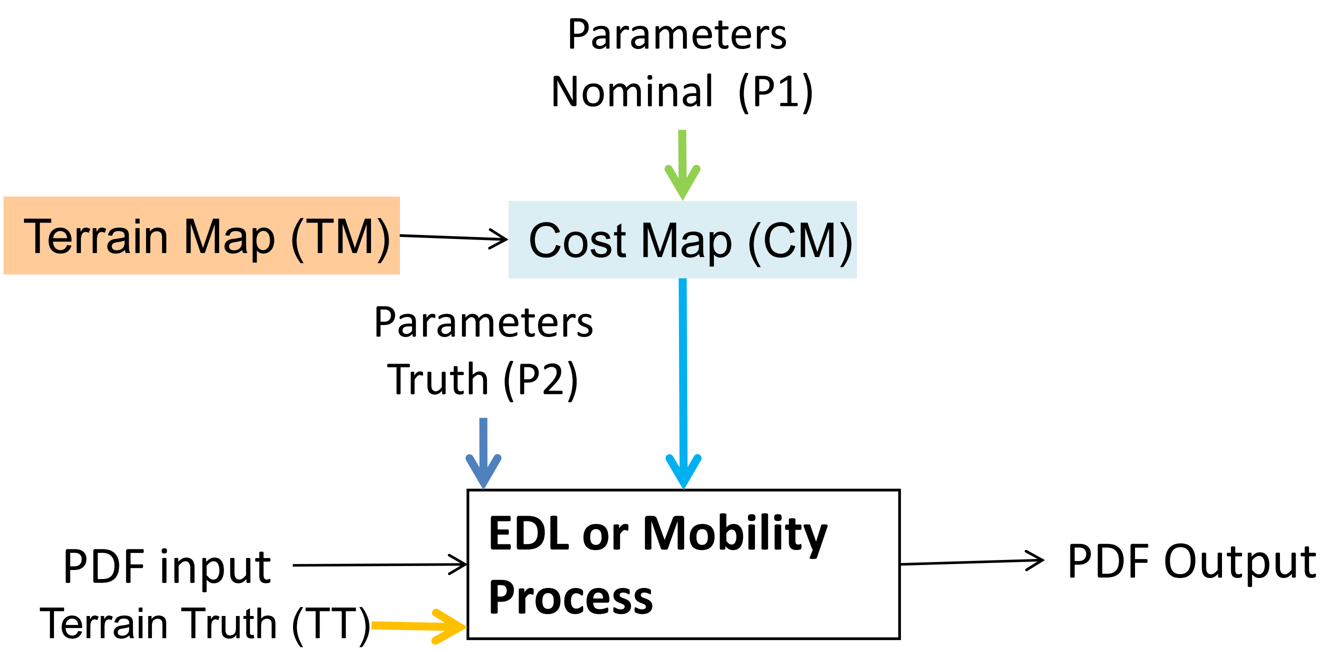
Parameters Cost Map

PDF input
(Landed State)

Mobility Process
-changes PDF by traverse path kinematics and drive/turn mobility dispersions due to slip and navigation errors

PDF Output
(Post-Traverse Distribution)

PDF Calculation – Single Stage

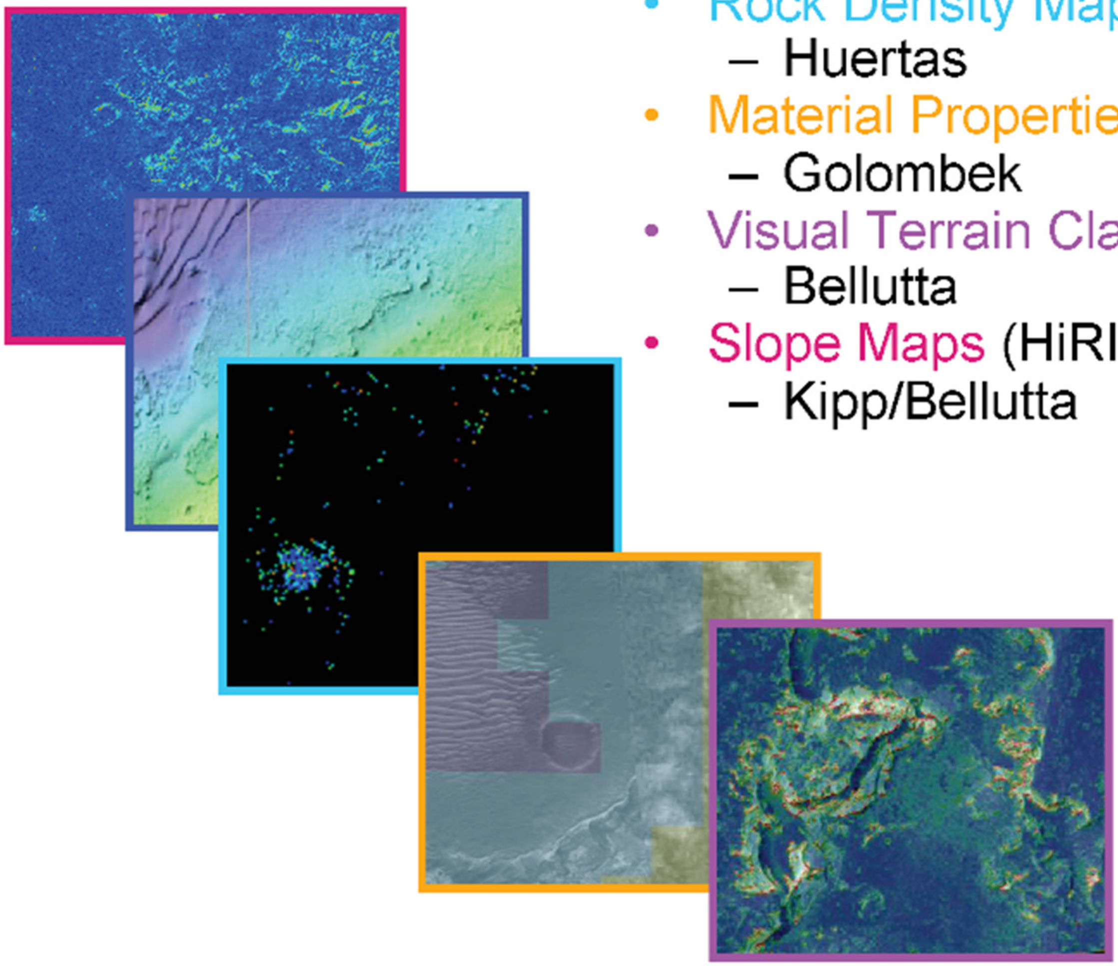


- PDF's may be User Prescribed; Analytically Derived; or Monte-Carlo Histogram Derived

PDF-Based Analysis

- Use PDF to **find expected values of key figure-of-merits**:
  - Mean landing fuel consumption under different Cost-Map logic
  - Mean rover traverse distance and traverse time
  - Expected mission life-time and distributions from PDFs of traverse-time and actuator time-to-failure, i.e PDF of $t = \min(t_{traverse}, t_{time\_to\_failure})$
- Determine **sensitivity to key mission & system parameters**:
  - Divert distance (fuel requirement) -- Landing accuracy
  - Drive speed -- Actuator failure model
  - Hazard thresholds (for landing and for rover) -- **EDL map size**
- Determine the effect of **environments**
  - Science target distribution -- Hazard distribution
- **Derive key decision parameters**:
  - **EDL targeting selection i.e. landing ellipse target placement**
  - **Optimum cache surface rendezvous target point**
- Analyze **effect of information gained** from successive sensing of terrain (e.g., prefer to drive previously seen terrain)

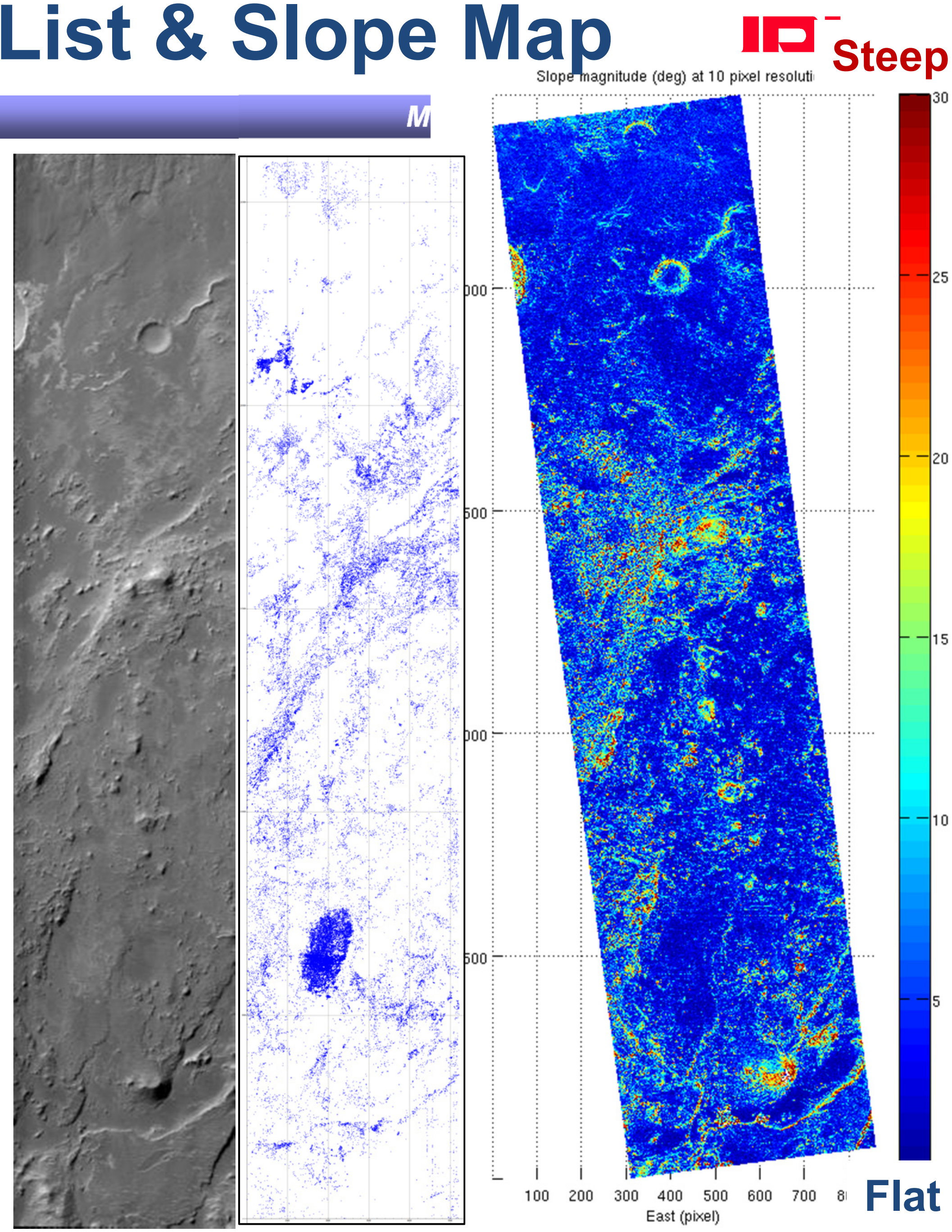
Available Mars Data Products



- Stereo Elevation Maps (HiRISE)
  - Kirk (USGS)
- Rock Density Maps (HiRISE)
  - Huertas
- Material Properties Maps (THEMIS)
  - Golombek
- Visual Terrain Classification (HiRISE)
  - Bellutta
- Slope Maps (HiRISE, USGS DEMs)
  - Kipp/Bellutta

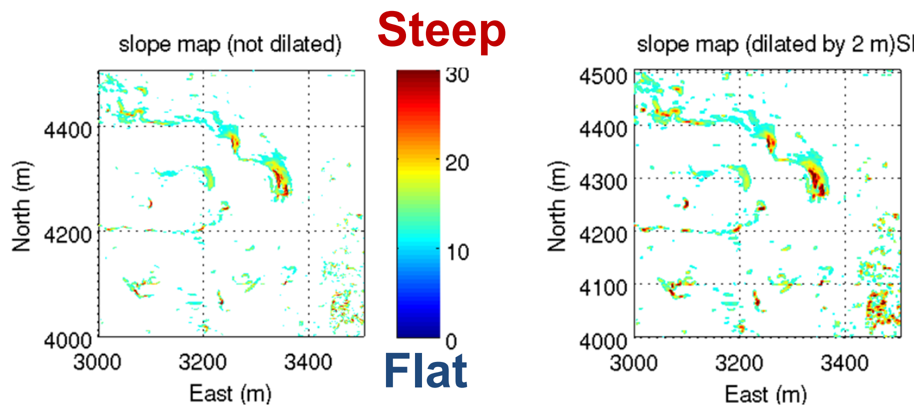
MRO Rock List & Slope Map

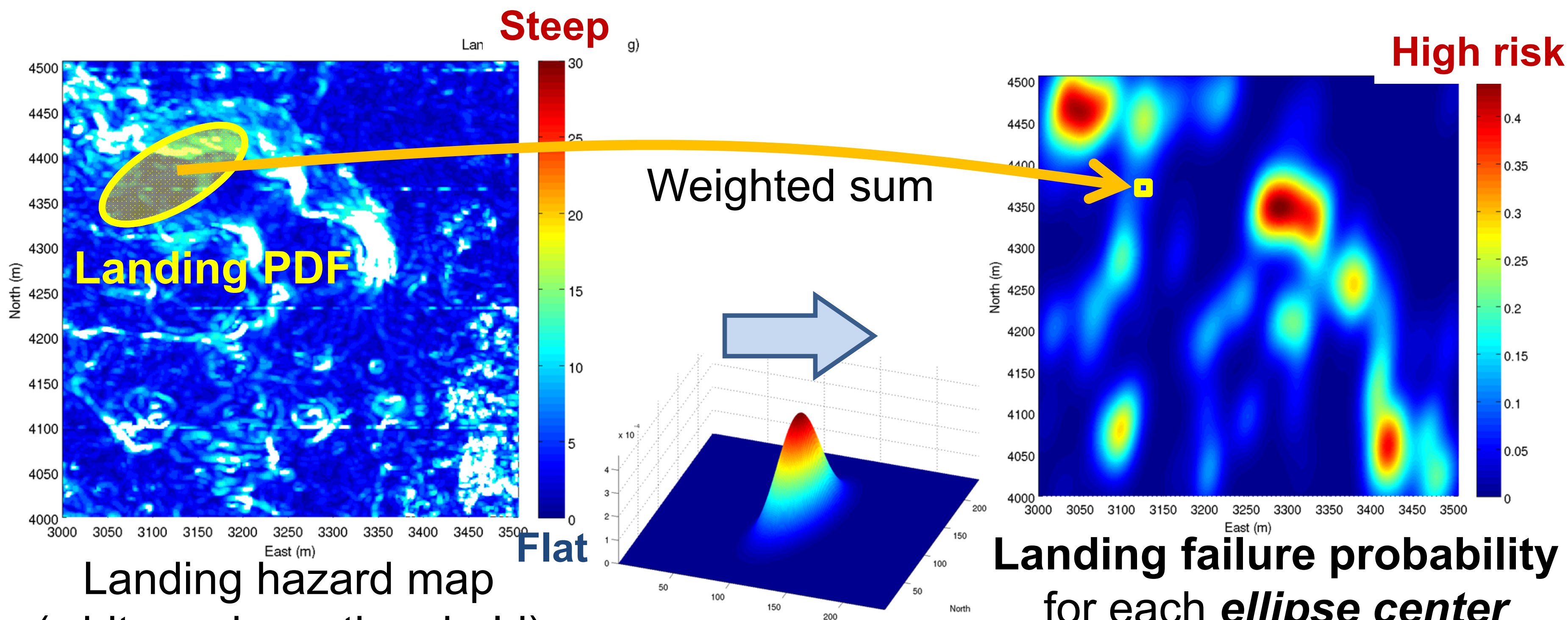
- Rock list
  - Image frame
  - Circular obstacles
  - 76,874 rocks in 5km-by-26km region
- Slope map
  - Geo-registered
  - Grid @1m resolution
- Registration error
  - Linear translation
  - Linear rotation
  - Other terms (neglected)



EDL without Divert

- Hazard list
- Dilate by lander radius
  → Lander treated as a point





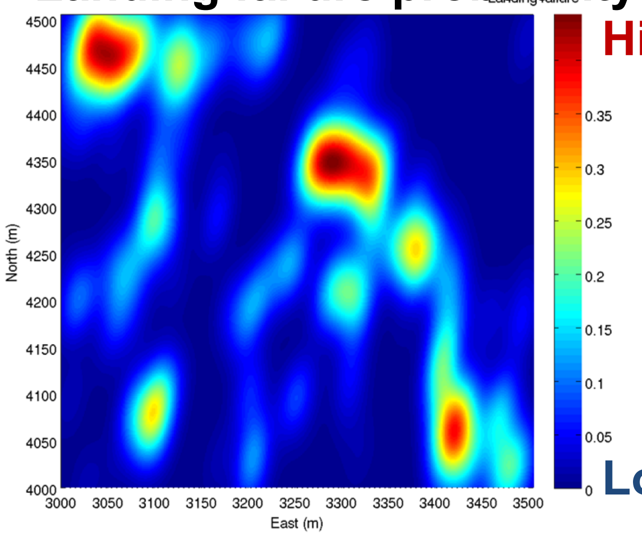
Landing hazard map
(white = above threshold)

Landing PDF

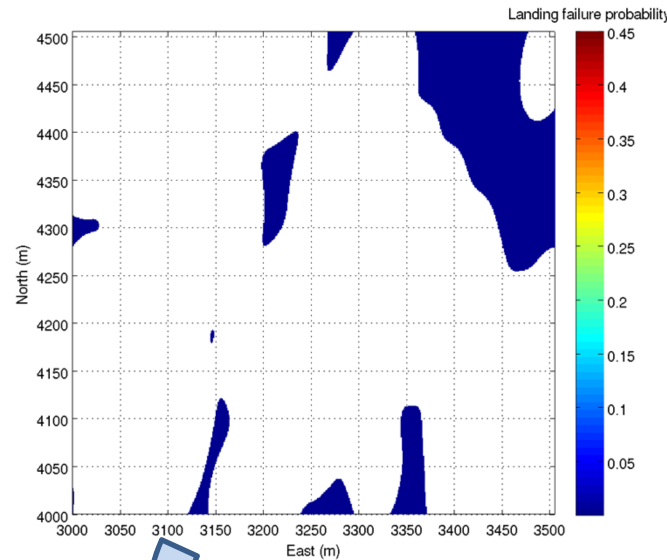
Landing failure probability
for each ***ellipse center***

EDL without Divert - Landing Ellipse Placement

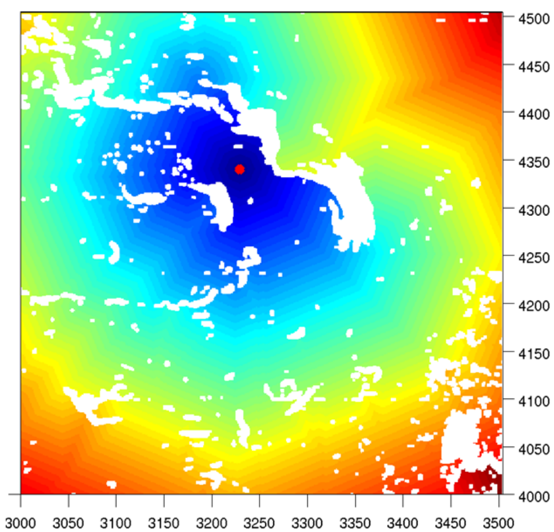
Landing failure probability



Thresholding

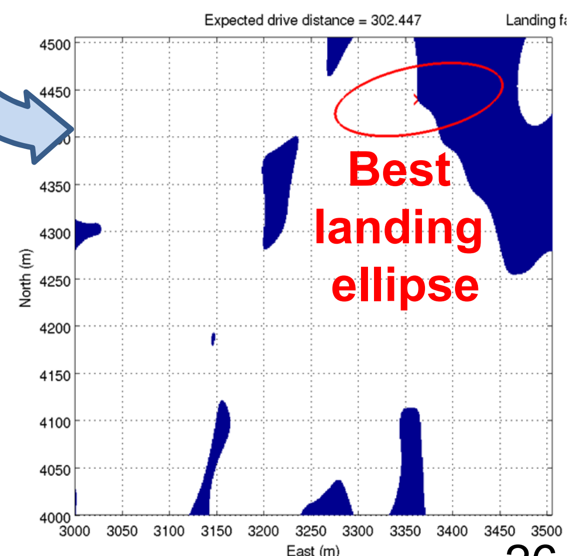


Mobility cost-to-go map

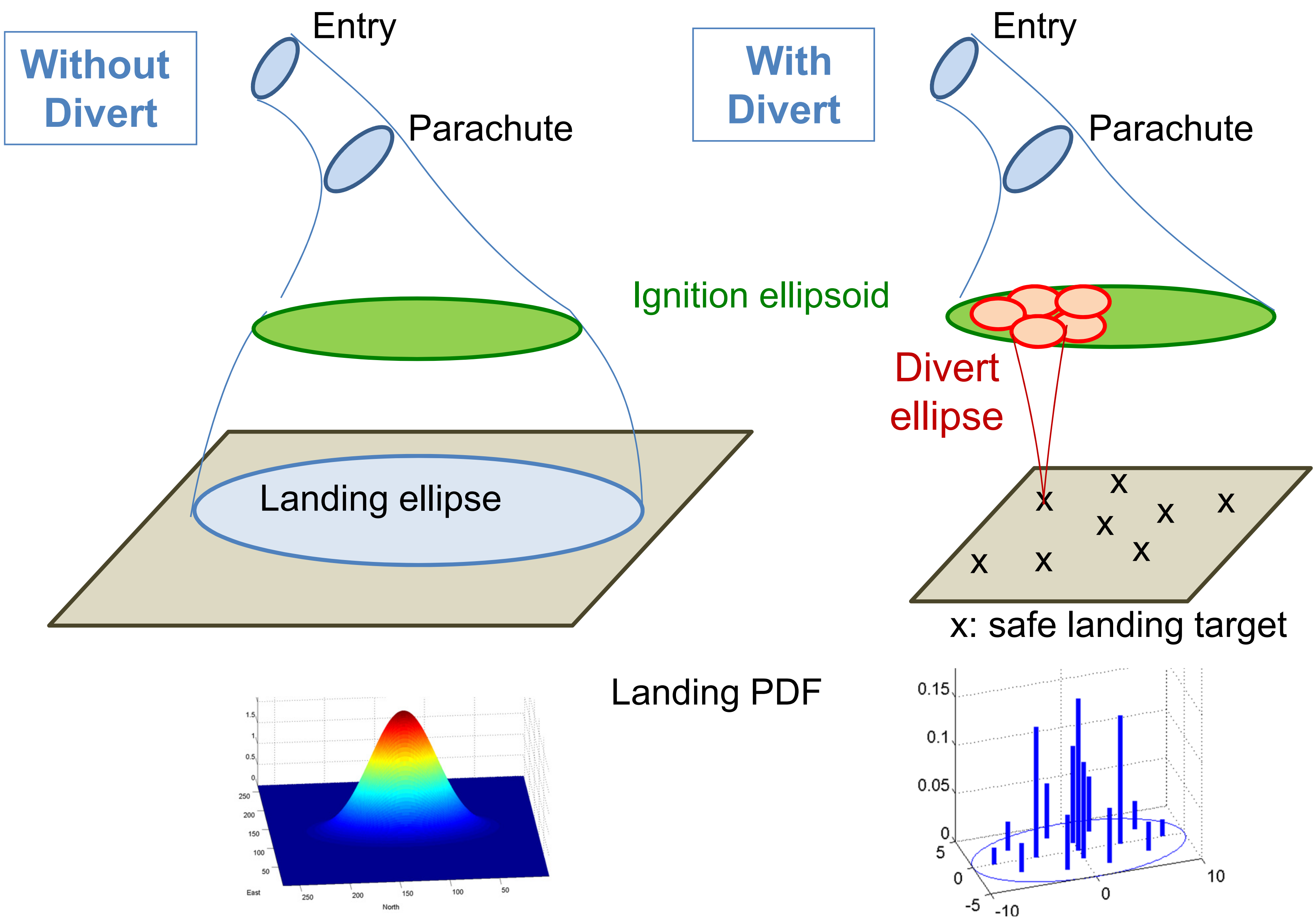


Close to target
Far from target

For each safe landing ellipse center, evaluate the **expected CTG** & **landing failure**, then pick the best ellipse

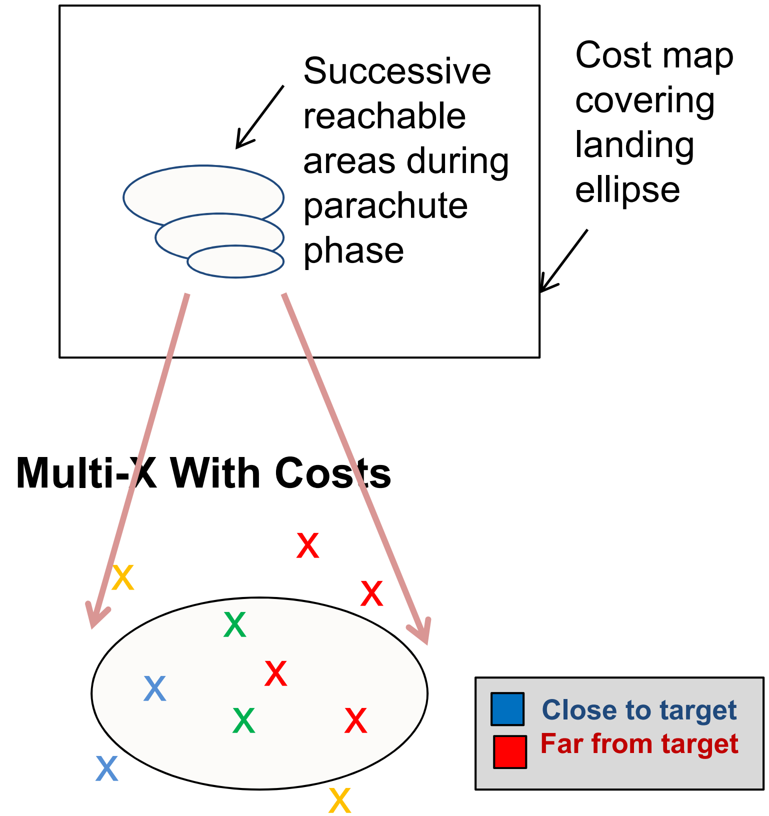


EDL Taxonomy



On-Board EDL Cost Map

- Map is iteratively used during parachute descent together with instantaneous **reachable footprint** of powered descent system to select & divert to landing target
- Map is simplified to a discrete set of landing targets "X" to simplify on-board, real-time use
- Lowest cost & reachable landing target is selected during parachute phase

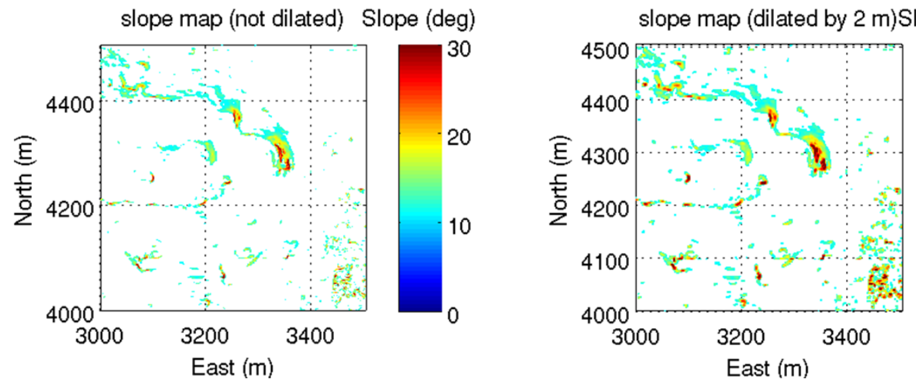


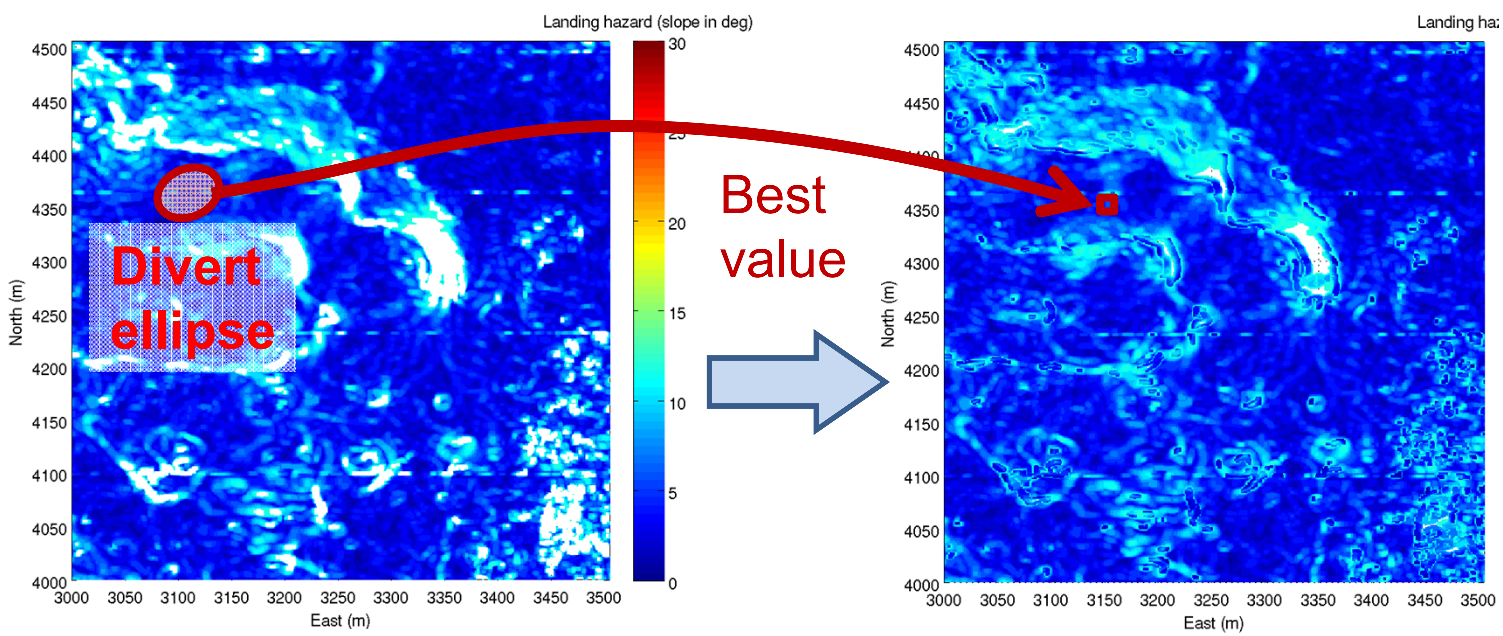
Pre-computed list of targets with costs.

Target list distribution is dense enough to guarantee at least one target within reachable zone.

EDL with Divert

- Start from the same hazard map
- Can divert to any point within the divert ellipse

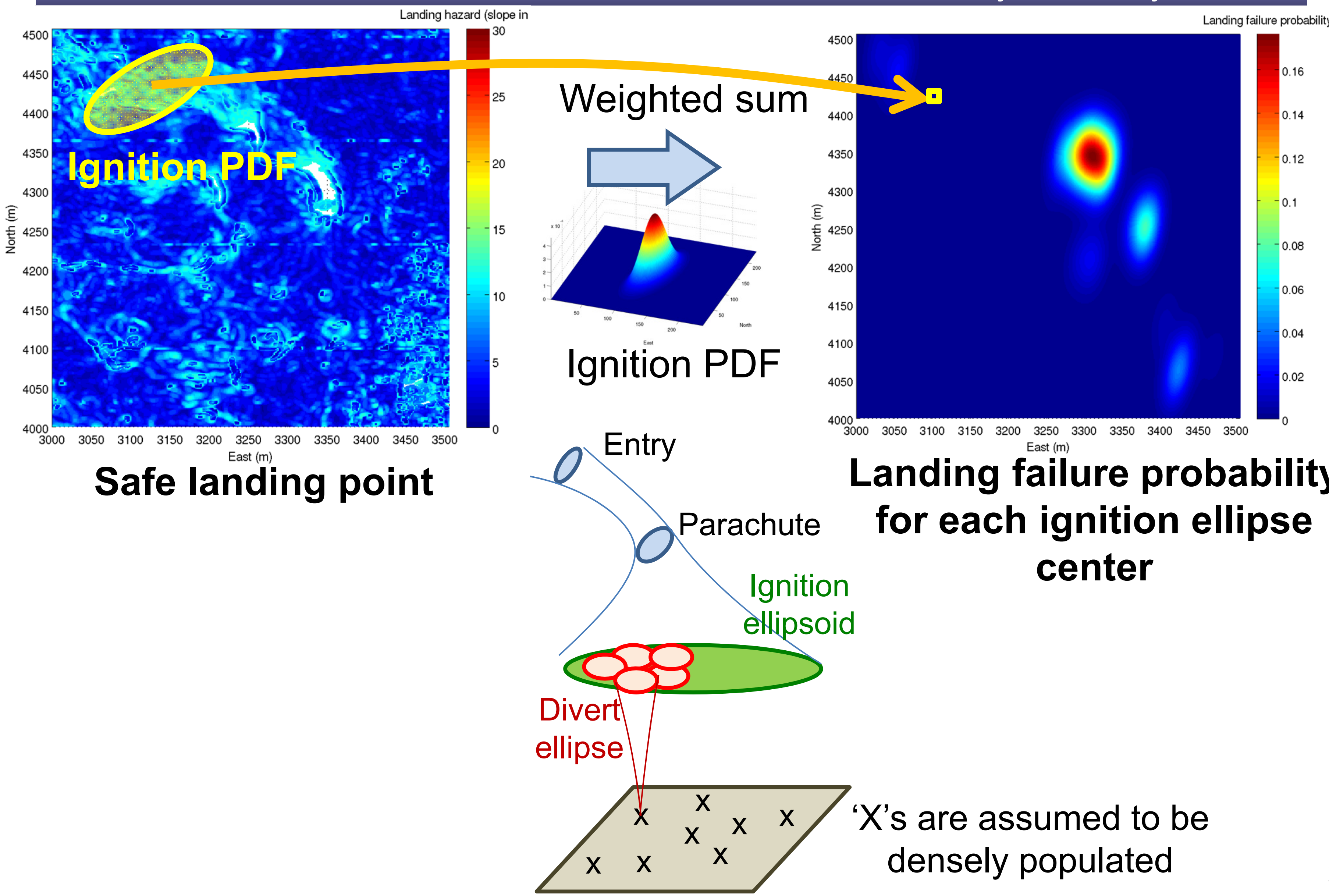




Color: safe
White:unsafe

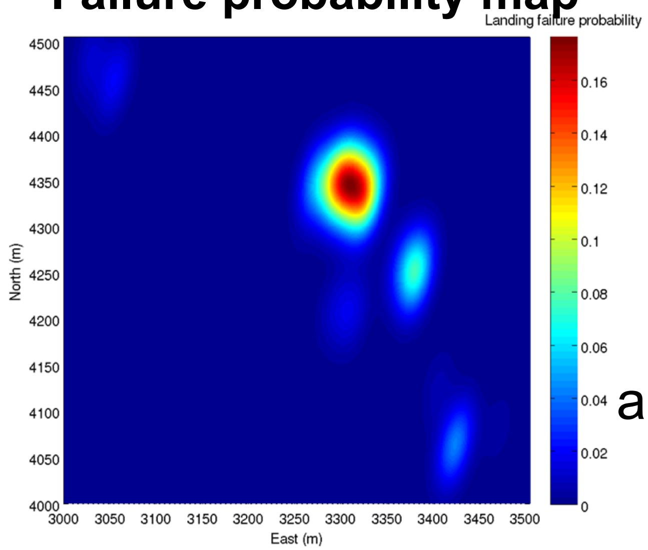
- Divert capability expands the safe landing region

EDL with Divert - Ignition Ellipse Placement

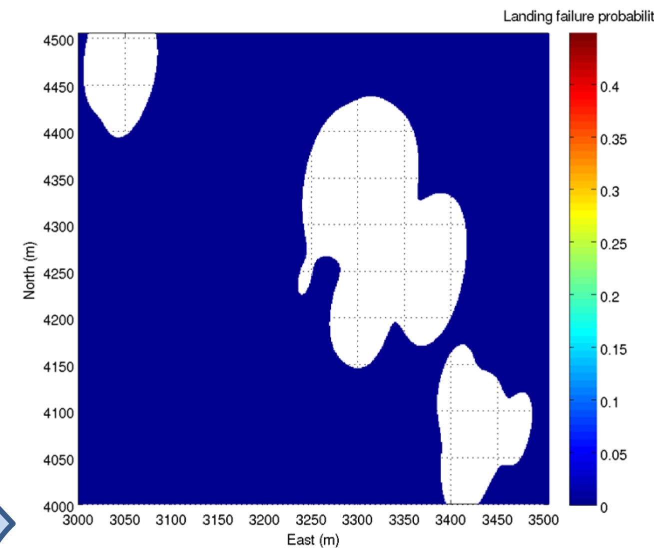


EDL with Divert - Landing Ellipse Placement

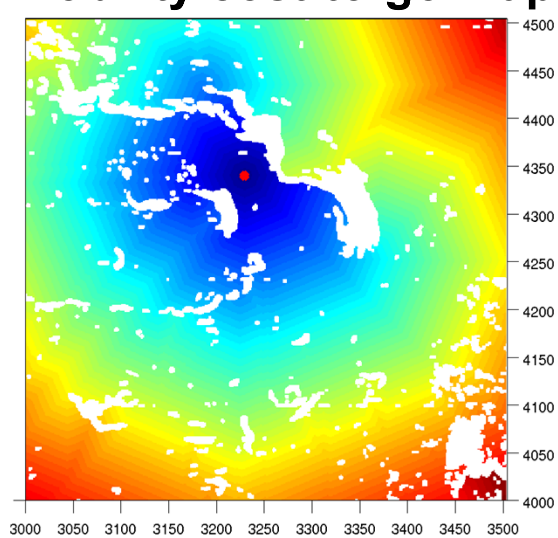
Failure probability map

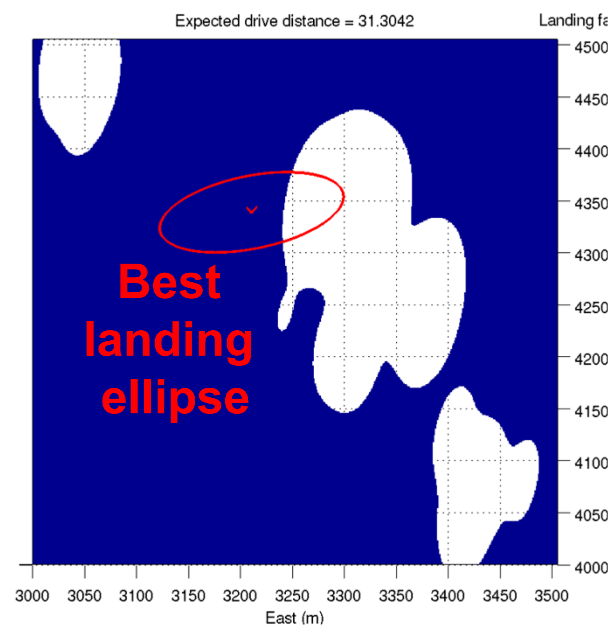


Threshold at accepted failure probability

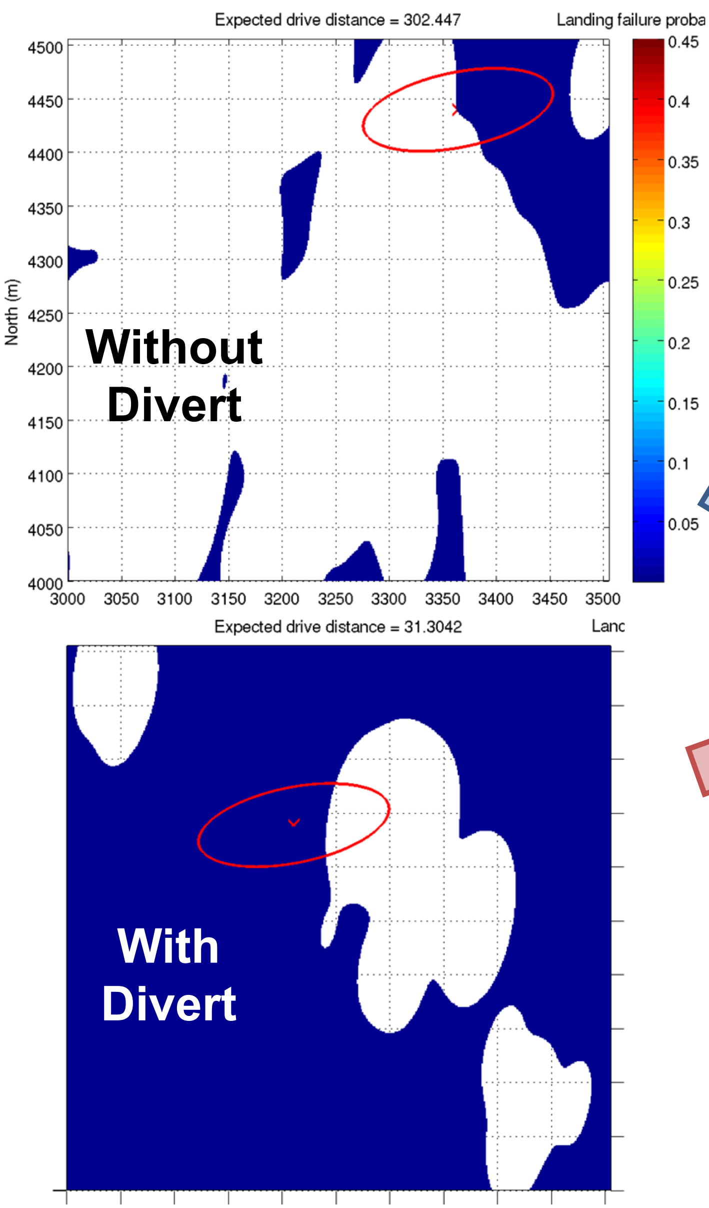


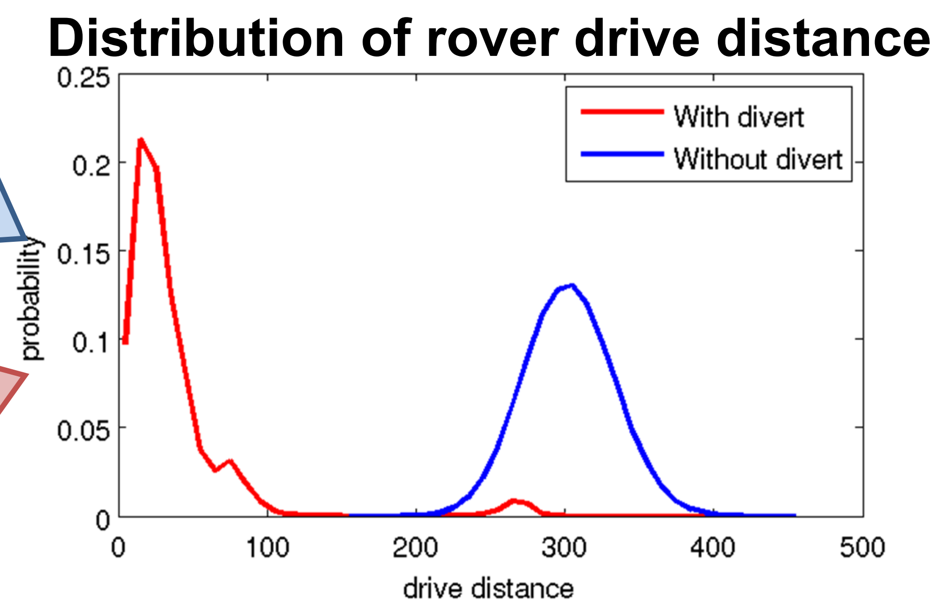
Mobility cost-to-go map





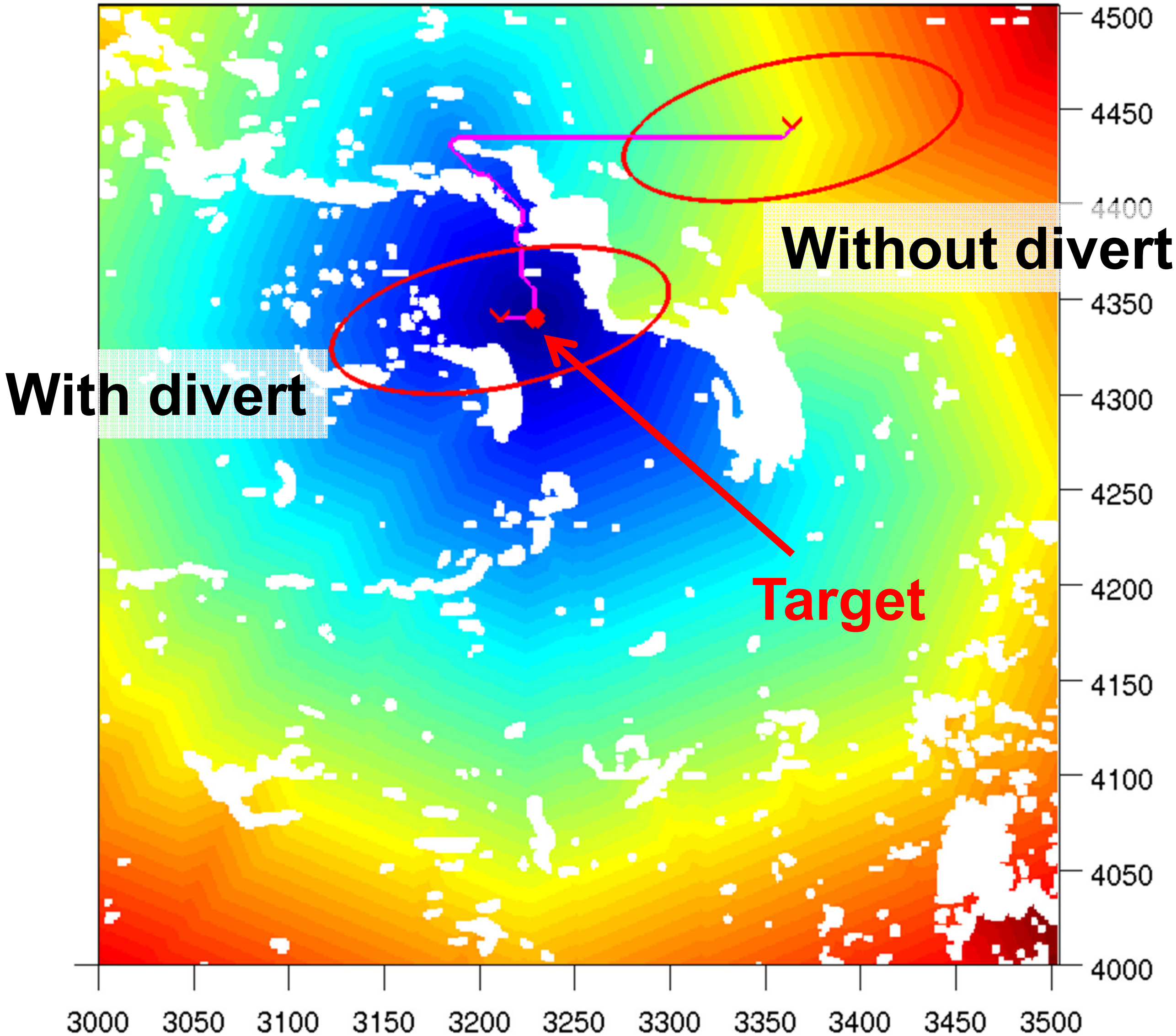
With and Without Divert





➔ Significant reduction with divert (90% in this example)

Representative Paths



Concolusion

- Extended **PDF methodology** familiar in EDL analysis to end-to-end Mars Rover mission using probability chains
- Introduced **Cost Map** concept as a unified method for describing staged decision making in EDL and Mobility
- Built a cost-to-go map for EDL use that captures a **key coupling between EDL & Mobility**
- Developed techniques select best **Landing Ellipse Target** based on both EDL & Mobility performance
- Future work
  - More realistic EDL model
  - Address **scaling and computational** issues - handling of large data sets, optimizing map resolution, adding user provided heuristics

Questions / Discussions